BacPack: Exploring the Role of Tangibles in a Museum Exhibit for Bio-Design

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ABSTRACT

We present BacPack, a tangible museum exhibit for exploring bio-design. BacPack utilizes tangible tokens on a large multitouch table display to allow visitors the opportunity to participate in a playful bio-design activity—engineering bacteria for sustaining life on Mars. To understand the role of tangible tokens in facilitating engagement and learning with the exhibit, we developed and evaluated two versions of BacPack: one with tangible tokens and one that consists of only multitouch interaction. Results from an evaluation in the Tech Museum of Innovation indicate that tangible tokens provide additional opportunities for collaborative problem solving and impact learning through support for tinkering and experimentation. We discuss design considerations for exhibits that facilitate creative engagement and exploration with biology.

Author Keywords

Tangibles; museum; children; bio-design.

ACM Classification Keywords

H.5.m. Information interfaces and presentation: User Interfaces---input devices and strategies, interaction styles.

INTRODUCTION

Biology has become a powerful technology in today's world, driving innovation in domains ranging from health, to agriculture, energy, and space travel. Considering the transformative impact of biology, it is important to expose the public to the burgeoning fields of synthetic biology, bioengineering, and biological design, inspiring the next generation of innovators to explore these cutting-edge fields. Our goal is to create educational activities that spark imagination and allow people of all ages to personally engage in creative problem solving with biology.

However, creating interactive and exploratory educational activities in biology is challenging due to the long time scales of living cells, the complexity of the topic, and the unique behaviors of biological systems, many of which occur at the nanometer level and are subject to unintuitive physics [19]. The unique aspects of biology—invisible medium, unintuitive behavior, slow response, and prescriptive experimental design—conflict with the goals of exploratory design-based activities, which require a tangible and responsive medium, and foster open-ended inquiry. Our approach combines virtual simulation with tangible tokens to bring the time and size scales of biology into the range of an effective exploratory learning activity.

In this paper, we present BacPack, an interactive museum exhibit that introduces core synthetic biology concepts to visitors through tangible and multitouch interaction. Similar to our previous work on SynFlo [18], BacPack bridges the size and time scales of biology by combining tangibles, animation, and simulation. However, while we designed SynFlo to allow users to experience the steps and actions of the experimental *process* of engineering living cells, BacPack focuses on highlighting the *application* of bio-design for solving real-world problems. BacPack engages users in problem solving through the design of bacteria, which are helpful for sustaining a research mission on Mars, providing a collaborative platform for creative engagement with digital biological creations.

This paper presents two primary contributions: (1) The design and implementation of a novel museum exhibit that utilizes tangible and tabletop interaction to engage the public in bio-design; and (2) Findings from an evaluation in the Tech Museum of Innovation focused on identifying the role of tangible interaction with passive tokens versus that of multitouch interaction with digital tokens in facilitating collaborative engagement and learning. We also share lessons from the iterative design and evaluation of our exhibit, including a discussion of design considerations for an exhibit that enables people to engage in creative problem solving with biology.

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RELATED WORK

Constructionist Learning

We designed and evaluated BacPack in collaboration with the Tech Museum of Innovation, whose philosophy is to "inspire the innovator in everyone" by encouraging people to learn by exploring and creating. The museum's philosophy and our design of BacPack draw upon Papert's Constructionist educational framework [19]. Constructionism asserts that children learn deeply when building their own meaningful projects in a community of learners, and when reflecting on the process. This framework is rooted in Piaget's [20] constructivism – which conveys the idea that children build knowledge through experience, emphasizing "learning by doing." Constructionism is often applied to learning in synthetic biology, where learners construct knowledge by solving real-world problems using a toolkit of biological parts [12, 22]. More generally, providing opportunities and tools to design, tinker with, and build has become an accepted framework for creative learning [21]. In the design of BacPack, we follow this approach—engaging users in designing and building (virtual) bacteria for solving real problems related to sustaining manned missions to Mars.

Tabletop and Tangible Interactions for Learning of Biological Concepts

Several projects have demonstrated the potential of applying TEI approaches to learning biological concepts. G-nome Surfer [23] and GreenTouch [25] are tabletop applications for collaborative exploration of genomic and phenology databases, which support open-ended inquiry. However, these applications are designed for formal learning at the college level. The DeepTree exhibit [6] is a multitouch tabletop interface that allows users to explore an interactive visualization of the Tree of Life, while Fishing with Friends [5] is a multiplayer exhibit where visitors play in a simulated fishing environment to learn about overfishing. Another application is Build-a-Tree, an interactive tabletop game for natural history museums [8].

A number of games have been written to engage players in the design of new organisms [Spore, Cubivore, Graffiti Kingdom], but few act as a platform for non-scientists that simulates tinkering and creating with actual biological material outside a wet laboratory setting. Most related to our work are the museum exhibits TrapIt! [13] and SynFlo [18], both deployed in the Tech Museum. TrapIt! [13] uses a touchscreen to control light beams that interact with live cells. Previously, our team designed SynFlo [18], through which museum visitors can experience the steps and actions of the biological engineering experimental process. With SynFlo, visitors use active tangible tokens (Sifteo cubes) embedded in authentic labware to imitate gestures scientists make in the lab, allowing them to experience the scientific workflow. While SynFlo and TrapIt! support collaborative, playful, and prolonged experiences exploring biological *phenomena* and *processes*, we designed BacPack to emphasize real world *applications*, encouraging visitors to engage creatively in problem solving through *design*.

Tangible Interaction for Learning

Much research has highlighted the benefits of tangible interaction for learning [3, 9, 15]. For example, Antle et al. [3] compared a tangible user interface to a mouse-based interface for jigsaw puzzle solving. They found that the tangible interface led to a higher success rate with faster success times, more communication, and more time spent actively interacting with the system. Similarly, Horn et al. [9] compared tangibles to a mouse-based graphical user interface in a museum exhibit, showing that using tangibles resulted in more participation. Horn et al. [7] also discussed several tangible and non-tangible versions of interactive learning tools and concluded that it is often a combination or hybrid of the two styles that is most effective. In the evaluation of SynFlo [18], we compared the use of abstract active tangible tokens (blocks) with the use of active tokens embedded in concrete authentic tangibles (labware). We found that the affordance of authentic tangibles encourages adult involvement and learning through observation compared to free exploration facilitated by the abstract tangibles. The evaluation of BacPack focuses on a different question – what is the role of passive tangible tokens in facilitating collaboration and learning in a problem solving and bio-design task, compared to multitouch interaction with digital tokens.

Ma et al. [14] compared tangible and graphical versions of an exhibit and found that while the tangible version attracted more visitors, there was not necessarily a difference in the visitors' experience with the exhibit. However, their exhibit utilized only three tangibles that needed to be shared among visitors. BacPack utilizes a set of 22 tangibles, which represent biological building blocks (genes); selecting and combining tangibles is a key phase in the BacPack activity. Our investigation focuses on understanding the role of tangibles in facilitating creative engagement and learning with the exhibit.

APPLICATION DOMAIN AND DESIGN GOALS

Synthetic Biology

Synthetic biology is an interdisciplinary field that combines engineering and biology. The field applies basic engineering principles such as standardization, abstraction, and modularity to the design of living organisms with new properties. Complex genetic programs are composed from standardized biological parts called BioBricks, which are used like "Lego Bricks". Synthetic biology aims to provide solutions to a wide range of real-world problems in areas such as agriculture, medicine, energy, and space travel.

Biological Design for Resource Utilization in Space

The premise of BacPack is that museum visitors take on the role of astronauts on an extended scientific mission on Mars. Visitors engineer bacteria that can help the astronauts by consuming resources that exist on Mars (e.g. soil, CO_2, biomass) and producing products that are required for sustaining human life on Mars (e.g. water, nutrients, O_2). This concept draws upon a known research paper, which quantifies the utility of synthetic biology techniques to harness available resources on manned exploration missions to Mars [17]. The paper discusses the importance of using synthetic biology to make Mars missions more viable by decreasing the amount of materials required to be sent to Mars. The authors propose to identify which molecules could be utilized to create desired products. BacPack mirrors this investigation by allowing visitors to experiment with biological designs of bacteria that consume different input molecules and produce desired output.

Design and Learning Goals

We designed BacPack in close collaboration with synthetic biologists and educators. The exhibit aims to introduce core concepts of synthetic biology to a general audience. We defined the following learning goals for BacPack: (L1) Demonstrate the principles of abstraction and modularity—genetic materials with documented functionality are used as standard biological parts, and are combined to create new biological systems; (L2) Facilitate the design and construction of genetic programs that include distinct input and output, and where output from one program serves as input to a different program; (L3) Communicate the basic steps of a synthetic biology protocol: constructing a genetic program, adding the program to a plasmid, inserting plasmid to a bacterial cell, testing for expected behavior; and (L4) Engage visitors in creative problem solving of critical challenges related to survival on Mars.

Our design goals for BacPack were informed by these learning goals and influenced by the Museum's constructionist educational philosophy: G1) Allowing people of all ages to design with biology; G2) Facilitating the development of inquiry skills through a hands-on playful experience; and G3) Providing opportunities for collaborative learning.

DESIGN ITERATIONS AND RATIONALE

Iterative Design

The current prototype of the exhibit, BacPack 2.0, is a result of an 18-month iterative design process. The premise of the exhibit is that museum visitors take on the role of an astronaut working in a research lab on Mars. The astronaut is tasked with engineering new bacteria, which could help the mission team to survive on Mars. The engineered bacteria consume resources that are available on Mars—such as CO_2, soil, and poop—and produce essential products—such as O_2, water, and biomass. The exhibit consists of an interactive tabletop combined with tangible tokens (see Figure 1a). The interactive tabletop is divided into two areas: a wet lab (on Mars) with four workbench stations, and the Mars landscape, which includes a biodome where astronauts make required products.

a)

b)

Figure 1. BacPack 2.0 (a), genes are represented by tangible tokens that visitors can place on the screen to make a selection. BacPack 2.1 (b), genes are represented by digital tokens dispersed along the edges of the screen. Visitors touch and drag the representations to make a selection.

Museum visitors use 22 tangible representations of BioBricks (i.e. genes) from the Registry of Standard Biological Parts [12] to design and engineer the bacteria. The goal of the activity is to increase the capacity of needed products. The quantity of products in the biodome is gradually reduced over time. Visitors are required to pick two genes, an input gene that consumes a particular resource, and an output gene that produces a product. These two genes are combined into a genetic program. Some combinations of input and output genes are more effective than others (i.e. produce more of the desired product). Figure 2 shows some of the possible combinations of resources and products.

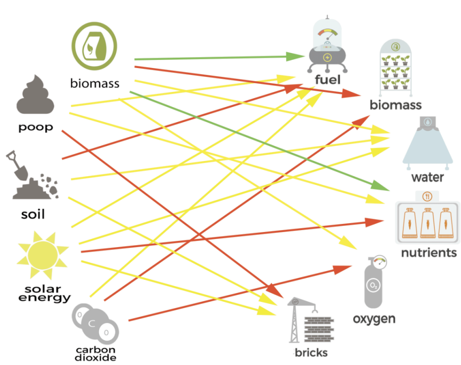

Figure 2. Subset of possible resource and product combinations; Color coded based on how many units are produced by each combination: green = 3 units, yellow = 2 units, red = 1 unit. Green combinations are most efficient.

Visitors then insert the genetic program into a digital plasmid by placing and wiggling/shaking the two genes on the screen surface. The visitors add the digital plasmid to a bacterial cell using a drag gesture, which results in multiplication of the cells and the growth of a colony of bacteria containing the genetic program. The visitors release the bacteria to Mars by dragging the petri dish with the colony towards the open Martian landscape. The bacteria gather around the resources they are consuming and produce a product that is added to products available in the biodome. An astronaut figure moves around the biodome, providing feedback to users about the effectiveness of the bacteria they created and indicating what products are most urgently needed.

To date, we have developed and evaluated three different prototypes of BacPack in the museum. The first prototype was designed as a facilitated exhibit that combines a digital lab and an actual web lab. The digital portion of the exhibit was similar in general to the current prototype but emphasized the process (i.e. lab protocol) rather than the design aspects of engineering bacteria. The wet lab portion was facilitated by two volunteers that helped visitors go through the experimental lab protocol of engineering bacteria. Based on an evaluation in the museum we decided to eliminate the wet lab activity, as it requires two facilitators and is time consuming. Instead, we redesigned the digital BacPack exhibit to encourage creative engagement by focusing visitors on the design of genetic programs rather than on the detailed protocol of inserting new genetic material into a bacterial cell. We abstracted some of the experimental protocol steps and eliminated virtual labware (e.g. beakers and flasks), and redesigned tangibles so that they are easier to grab and include a visual reference to DNA. We introduced a digital representation of a plasmid (i.e. ring of DNA), which carries the genetic program created by the users into the bacterial cell, as the main focus of the tabletop interaction. We also added a history tab with information about genetic programs created by previous visitors to inform and inspire current users.

Following further evaluation, we introduced more narrative in the activity using an astronaut character to motivate visitors by highlighting needed products. The astronaut character helps visitors start the activity and aids visitors in design optimization by providing concrete feedback about the effectiveness of their genetic program.

To explore the role of the tangible tokens in facilitating engagement and learning, we created an alternative prototype of the exhibit, BacPack 2.1, in which the tangibles were replaced with 22 digital tokens that could be moved and rotated via touch. Figure 1b shows BacPack 2.1. The Observational Study section describes the procedure and results of comparing these prototypes in the museum.

Implementation

BacPack was developed on the 55” MultiTaction Cell. It was programmed in JavaScript using the Multitouch Cornerstone 2 SDK. Tangibles were assembled from laser-cut acrylic layers and incorporated into the design using the MultiTaction fiducial markers.

Design Rationale

We encountered several challenges in the design of BacPack, which are common when designing museum exhibits for direct interaction with biological entities. Here we describe the choices we made to address them. Our design choices were informed by user feedback we received through our iterative design process as well as by other museum exhibits [13, 18] and by frameworks for learning with interactive surfaces and tangibles [1, 2].

Supporting social scalability – Based on the museum philosophy and on exhibit design principles [11, 24] our exhibit aimed not only to accommodate multiple people but also to enhance visitors’ experience through collaboration. BacPack provides four virtual workbenches where visitors can work in parallel on different biological designs. The application invites all users to release their engineered bacteria to a common environment (i.e. Mars landscape) and observe the impact. Users are encouraged to collaborate on solving pressing problems (e.g. lack of oxygen) as well as to draw upon bio-designs (i.e. genetic programs) created by previous visitors. The tangible bio bricks provide multiple access points [10], allowing visitor groups to collaborate while working within the same station.

Overcoming time and size scales - Bio-design activities typically require time on the scale of days in order to allow for cell transformation. In the exhibit, we chose to implement a virtual workbench on an interactive surface, where animation is used to bridge the time scale from days to seconds through simulation. To represent genes (i.e. sequences of DNA with specified functionality) we draw upon the metaphor of BioBricks, which is widely used within bio-design [12]. BioBricks embody three engineering principles that are important in synthetic biology: abstraction, standardization, and modularity. We decided to use tangible representation for BioBricks in order to allow for physical interactions that support experimentation and learning [4]. The form factor of the tokens reinforces the metaphor of BioBricks; the shapes of the tangibles reflect the symbols used for depicting genes in real bio-designs. The touch-based gestural interactions (wiggling, dragging) were implemented to mimic physical aspects of laboratory work that include manipulating liquids through shaking, and pouring.

Fostering strategy development – The goal of the exhibit, survival on Mars through efficient utilization of resources, aims to encourage problem solving and strategy development. We chose to provide tangible tokens to encourage tinkering and experimentation with BioBricks and bio-design. To further help visitors develop a strategy within the activity’s short time span, we provide users with contextual hints (through the astronaut character), as well as a dynamic simulation of resource depletion and production.

Facilitating learning in informal settings - Interactions with museum exhibits are typically short and casual. To allow visitors to learn even from a brief experience, we designed BacPack so that initial success could be achieved within a short time frame. We designed the core activity—creating a genetic program, inserting it to a cell, and releasing to Mars—to be quick and exciting, yet at the same time visitors are exposed to core principles of bio-design. The visibility of the tangible and gestural interactions allows for learning through observation before or while visitors actively engage with the exhibit. The use of physical actions (grabbing, combining, placing) and gestural interaction (wiggling, dragging) facilitates *learning through doing,* helping visitors to develop a conceptual model that is connected to the processes and applications of bio-design. Visitors that engage with the exhibit for extended periods are exposed to additional layers of complexity. The exhibit does not present formal game levels but rather allows visitors to discover the complex relationships between resources, genetic programs, and the Martian environment.

OBSERVATIONAL STUDY

To understand how our design decisions influenced interactions with the exhibit, we conducted an observational study in the Tech Museum of Innovation. To explore the role of the passive tangible tokens in facilitating engagement and learning in a problem solving and bio-design task, compared to multitouch interaction with digital tokens, we tested two different prototypes: BacPack 2.0 (Figure 1a), which uses tangible tokens, and BacPack 2.1 (Figure 1b), which supports multitouch digital tokens.

Procedure

We deployed BacPack in the Tech Museum of Innovation over four days. We ran the study on two weekend days (Saturday, Sunday) and two weekdays (Tuesday, Wednesday) for a total of 4 hours with BacPack 2.0 (tangible tokens) and 3.5 hours with BacPack 2.1 (virtual tokens). Both interfaces were tested on each day. For each visitor group, a facilitator seated behind the tabletop invited the visitors to build bacteria for Mars. The facilitator then pointed to the tokens around the table, explaining that they were genes to be selected from, and that these genes would tell their bacteria what to do. The facilitator then encouraged the visitors to choose two genes and insert them into the plasmid. The facilitator would step in to help visitors when needed.

After visitors completed the activity, the facilitator conducted a debrief - asking child visitors their age, questions to assess their understanding of the biological process, and to rank on a scale of 1 to 10 how difficult they thought the exhibit was and how much they enjoyed interacting with it. We used a video camera on a tripod to record the interaction on and around the tabletop surface.

Data Analysis

Video recordings were split into segments by the facilitator based on visitor group. We used Atlas.ti to analyze 16:16:42 hours of clips using a video coding scheme informed by existing frameworks [1, 13, 18] and developed iteratively based on interactions found while observing the videos. Based on emerging themes, we eventually consolidated our observations into 12 codes, each representing a different higher-level theme. Inter-coder reliability among three coders based on 62% overlap was very good with an intraclass correlation coefficient of 0.98. Video coding data was analyzed using SPSS. Independent samples t-tests were used to compare means between groups and chi-square tests for independence were used to determine significance between conditions for categorical variables.

Results

Participation

Over the four days of the study, 103 visitor groups interacted with the exhibit, accounting for 193 users varying in age from 4 through adulthood. We alternated between the tangible and multitouch versions in an attempt to observe a similar number of groups between the two prototypes. However, because the number of visitors in the museum varied dramatically even throughout a single day due to the large number of organized group visits, our data includes an uneven split across the two versions: 65 groups interacted with the tangible version of BacPack but only 34 with the non-tangible version.

Several groups and individuals were excluded from video coding measures due to camera obstruction or a lack of meaningful engagement due to young age. However, demographic measures are still reported for these groups. Additionally, four groups sought out and interacted with both versions of the exhibit and thus were excluded from comparative analyses. Table 1 describes group composition per condition. There were no significant differences in group composition, nor group size, age, or gender ratio.

Holding Time and Progress

We measured holding times from the time the first visitor in a group approached the exhibit to the time that the last visitor in that group left the exhibit. In both versions of the exhibit the average holding time was more than 4 minutes, indicating that our exhibit could facilitate active prolonged engagement (APE) [11]. In both versions about 20% of the groups interacted with the exhibit for more than 7 minutes. There were no significant differences in holding times between the two versions. Figure 3 shows a histogram of holding times for visitor groups per condition.

In both versions of the exhibit, almost all groups (tangible: 56/59 groups, 95%; multitouch: 31/34 groups, 91%) completed the activity successfully at least once - deploying engineered bacteria to Mars and watching their impact. Table 2 summarizes success and holding times by condition.

Group Composition	BacPack 2.0 (Tangible Tokens)	BacPack 2.1 (Multitouch Tokens)
One child	24	9
One adult	13	11
One child + one adult	5	1
Multiple children only	15	9
Multiple adults only	2	1
Group size	N = 65, M = 1.24 (1.45)	N = 34, M = 2.03 (1.45)
Total adults (18+)	29 (13 female)	21 (6 female)
Total children	86 (59 female)	48 (30 female)
Age (children)	N = 38, M = 10.55 (2.25)	N = 53, M = 10.49 (2.83)
Total groups	67	36

Table 1. Group composition by condition

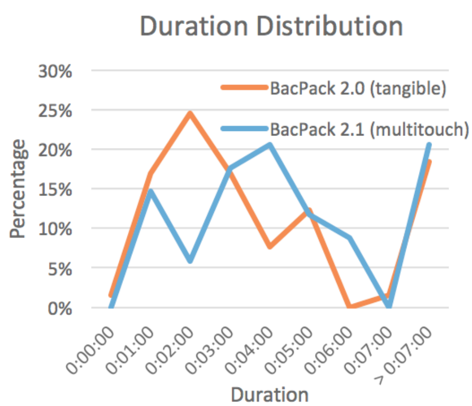

Figure 3. Histogram of holding times for visitor groups per condition

Apprehendability

To assess the apprehendability of the exhibit, we looked at temporal and subjective measures. We measured time to first touch as the time passed from a visitor's initial approach to the exhibit to first active interaction with the exhibit. On average visitors time to first touch was 15.7 seconds, and average time to first success was 1:16.02 minutes. There were no significant differences in these measures between the two versions of BacPack (Table 2).

In the debrief, we asked visitors to rate (on a scale of 10) how difficult it was to interact with the exhibit (see Table 2), users from both conditions generally responded that the exhibit was not very difficult to figure out and interact with. However, one 8-year-old who engaged with the tangible version explained in more detail that he felt the functionality was really easy but that the concept was really hard.

	BacPack 2.0 (Tangible Tokens)		BacPack 2.1 (Multitouch Tokens)		
	N	**M (SD)**	**N**	**M (SD)**	**p**
Minutes to first success	56	1:14.81 (0:51.15)	31	1:18.20 (0:43.15)	.742
Minutes to first touch	59	0:17.25 (0:46.88)	34	0:32.71 (1:52.12)	.355
Overall holding time (Minutes)	59	4:44 (5:52)	34	4:40 (3:14)	.961
Enjoyment	51	7.41 (2.01)	42	7.07 (2.26)	.436
Difficulty	50	3.40 (2.45)	39	3.64 (2.35)	.641

Table 2. Success and interaction by condition, as well as attitudes of users on a 10 point Likert scale

Enjoyment

Many visitors expressed enthusiasm towards the exhibit. Four groups even returned to try a version of BacPack they had not seen yet. Responding to debrief questions, users of both versions of BacPack reported positive enjoyment, and there was no significant difference between the two conditions (see Table 2).

Strategy

To identify cases when visitors applied basic strategy to their bio-designs and problem solving, we looked at verbal utterances among group members. In one group (G3, tangibles, 38:07 minute visit), we saw the following exchange: A: "We need more biomass." B: "Wait. What do we need? What is this? [Points to biomass on Mars.]" A: "Biomass" B: "Oh. We need biomass?" A: "Yeah." B: "Produce, if there is biomass, OK, I've got this." We also encountered children conveying their current state and the state of the system to the group: "We've got a bunch more bricks coming. Uh oh. We need water." (G7, multitouch, 22:06 minute visit).

In addition to verbal utterances, we also looked at physical indicators such as searching for particular genes around the exhibit (rather than simply combining any two available genes). Although in both conditions about half of users physically moved their hands or actively looked around their vicinity as they decided which genes to use (tangible: 55%, 57/103; multitouch: 53%, 35/66), significantly more people physically reached outside of their immediate area to acquire tokens in the multitouch condition (42%, 28/66) than in the tangible condition (27%, 28/103). From observations, we saw that reaching for distant tokens located on the bezel in the tangible condition often meant reaching around the table or physically walking to a new location, while for multitouch tokens users could reach directly across the table surface, which could potentially explain the disparity. However, the need to reach further to access tangible tokens created opportunities for collaborative engagement, as described in the next section.

Figure 4. (left) A child holds two tangible tokens up to each other in the air. He performs this action four times in a row, each with a different token in his left hand, before deciding on a combination to place on the screen. (right) A child passes a pair of tangible tokens to a child at a neighboring station.

While visitors were free to manipulate tokens in both versions of BacPack, we found that only the tangible version exhibited epistemic exploratory action. Visitors would pick up physical tokens and experimentally place them next to others in the air, trying different combinations, before committing to a particular combination of genes and placing it on the surface (Figure 4).

In some groups (4%, 4/107), visitors actively engaged with multiple stations at once. In one group (E1, multitouch and tangibles, 24:02 minute visit), a visitor stood in front of one station and occasionally reached over to the neighboring station to complete a round there. When the exhibit started to get more crowded, she moved to the neighboring station permanently. In another group (OP, tangibles, 22:06 minute visit), a visitor stood between two stations and alternated during the time an animation played.

Collaborative Engagement

The exhibit supported multiple visitors while facilitating parallel work, peer support, and rich collaborative engagement. In 47% (48/103) of the groups (tangible: 45%, 30/67; multitouch: 47%, 16/34, and 2/4 who tried both versions) visitors worked in parallel. We also found evidence for peer support and for learning through observation. In about 30% (30/101) of groups we saw learning through observation, where visitors watched a parent or peer at least briefly before starting to interact with the exhibit. Throughout the interaction with the exhibit, in about 45% (18/40) of groups we identified peer support in the form of physical intervention (e.g. pointing to a particular object or area on the tabletop), as well as direct assistance (e.g. to help touch input). Such peer support was more prominent with the tangible version (54%, 14/26) than the multitouch version (29%, 4/14), although the difference was not statistically significant.

In general, we identified several peer collaboration patterns: working together (handing pieces, giving verbal suggestions or instructions both within and between stations); working in parallel (side by side independent work, occasionally helping a peer or reaching over to a different station to acquire a token); and sharing a station (interacting together within the same station).

One interesting subset of collaboration scenarios occurred during gene selection. Sometimes support during selection arose from a parent who offered a potential gene or pair of genes to a child actively engaged in the exhibit. In one case (G1, tangible, 5:18 minute visit), a father walked around the table to pass a tangible token to his daughter at the other end, who in turn offered it to her brother, the one actively interacting with the exhibit. Support can also come from peers. In one case (G2, tangible, 5:14 minute visit), a girl asks another across the table what tangibles are visible from the other's vantage point.

We also found fluidity in support roles. For example, in one group (G2), a father walks over to the exhibit and start interacting. His son quickly takes over the station and the father takes on a support role. His daughter, who had been working at her own station, eventually comes over to take over for her father as the son's main supporter. Another example includes a group of 7 school-aged girls (G5, multitouch, 10:21 minute visit) who initially had to double-up on some stations. As some group members lost interest, the others began to spread out until each had her own station. Although they had the opportunity to work in parallel, they chose to continue to verbally strategize.

	BacPack 2.0 (Tangible Tokens)		**BacPack 2.1 (Multitouch Tokens)**		**Overall**	
	N	**Count**	**N**	**Count**	**N**	**Count**
Mars	35	11	20	12	55	23
Bacteria	35	14	20	4	55	18
DNA	35	3	20	0	55	3
Plasmid	35	1	20	1	55	2
Make	35	7	20	9	55	16
Gene	35	8	20	2	55	10
Combine	35	1	20	1	55	2
Product / Resource Names	35	2	20	1	55	3

Table 3. Dialogue analysis: open answers that include the term

Learning

To assess learning, we asked visitors open-ended questions after they completed interacting with the exhibit, getting visitors to describe the exhibit in their own words. We quantified the number of relevant biology and domain terms used (Table 3). Interestingly, in the multitouch version we see more use of the terms "Mars", "plasmid", "make", and "combine", while in the tangible version we see more "bacteria", "DNA", and "gene". In particular, visitors who used the multitouch tokens used the terms "Mars" (χ^2 (2, N = 55) = 4.27, p = 0.039) and "make" (χ^2 (2, N = 55) = 3.86,

$p = 0.050$) significantly more than those who encountered the tangible tokens. There were no significant differences for the other five terms. However, the differences in terminology used suggest that the two versions result in somewhat different learning outcomes: the tangible version focuses on the design problem and the elements of the genetic program, and the multitouch version highlights process and context.

Aside from using relevant terms, visitors showed a grasp of the learning goals through their overall response to post-task questions. For example, "[The goal is] Helping to survive on Mars" (multitouch, age 9); and "I'm making bacteria to go on Mars, so I choose something and make something else. Yeah. Telling you what we need" (tangibles, age 9). Visitors were also able to describe aspects of the process. For example, "I found that the poop is the best thing to make water and the energy" (tangibles, age 11). We also found some evidence for inquiry and reflection during the interaction. Children sometimes read the science-term-laden text on screen out loud and occasionally asked the facilitators questions like "Why are we sending bacteria to Mars?" (tangibles, age 9).

DISCUSSION

We performed an on-site evaluation of two versions of the BacPack museum exhibit: BacPack 2.0 (tangible tokens) and BacPack 2.1 (multitouch tokens). Our investigation focused on how our design choices support the exhibit's learning and design goals. In particular, we were interested in the role of the tangible tokens in supporting engagement and learning in a bio-design task compared to the use of multitouch digital tokens.

In both versions of the exhibit, visitors of all ages collaborated with friends, family, and strangers, sometimes for extended periods of time and overall expressing a positive impression of their experiences (G1, G3). Despite the general perception that the activity was relatively easy, it proved challenging enough to provide opportunities for collaboration not just among active users, but also from visitors who were observing the interaction and serving a supportive role like parents and caretakers. While we did not find statistically significant quantitative differences between the two prototypes of BacPack, we identified several more nuanced qualitative differences between the tangible and multitouch prototypes.

First, we observed that in general the exhibit was able to effectively facilitate a variety of collaboration styles and fluid role switching. In particular, the tangible tokens created opportunities for collaboration beyond those afforded by the multitouch only version. For example, because the tangible tokens were spread around the bezel, often out of immediate reach for a particular user, people asked for help from other users. Placing the tangible tokens around the interactive surface also encouraged observers (e.g. parents) to reach out to the tokens and suggest them to users.

Second, we found that the tangible tokens allowed users to tinker and experiment independent of the steps needed to progress through the exhibit in ways that we did not observe with the multitouch users, thus facilitating physically distributed learning [16]. We identified several epistemic actions taken by users on the tangible prototype that are similar to those outlined by Antle et al. [1] including *spatial arrangement of tokens* and *comparing alternative combinations of tokens.*

Third, we found strong evidence for learning and inquiry in both versions of the exhibit (G2). However, we did see differences between the tangible and multitouch prototypes in the learning concepts visitors retained, as evidenced by the terminology used and comments visitors made in the debrief. With the tangible version, visitors more readily used terminology like "gene" and "bacteria" and contributed comments about the combination of genes they made, the process of inserting a genetic program to the bacterial cells, and the effect of particular gene combinations (L1, L2, L3, L4). Visitors who engaged with the multitouch version focused more on "Mars" commenting more broadly on the impact of made products on Mars (L3, L4). We hypothesize that through physical interaction with the tangible tokens, visitors developed a conceptual model that explained the role of genes and bacteria, which are represented by the tangible token interactions.

Taken together, these findings, while not conclusive, indicate that tangible tokens provide further support for learning as well as more opportunities for collaboration.

CONCLUSION AND FUTURE WORK

TEIs play a major role in creating educational activities that spark imagination and allow people of all ages to experience creative problem solving with biology. We presented BacPack, a tangible museum exhibit for exploring bio-design, which utilizes tangible tokens on a large multitouch table display to allow visitors to participate in a playful bio-design activity - engineering bacteria for sustaining life on Mars. We discussed design considerations for interactive exhibits, which foster creative engagement with biology, and investigated the role of tangible tokens in facilitating collaborative learning in such exhibits. We showed that tangible tokens provide additional opportunities for collaborative problem solving and impact learning through physical interaction and support for tinkering and experimentation.

Future work will continue to draw upon TEIs to provide young children with educational activities that encourage creative problem solving with biology, support open-ended inquiry, and facilitate collaborative exploration of concepts previously considered too complicated for children.

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